Neutron-antineutron oscillation search in DUNE with convolutional neural networks

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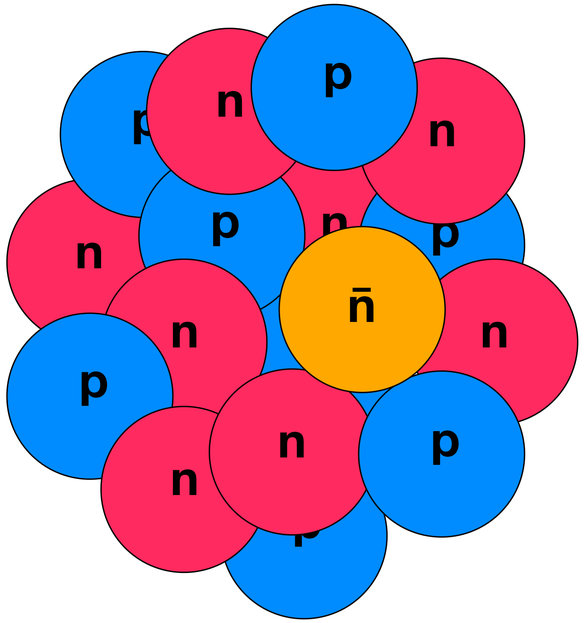
Neutron-antineutron oscillation

- **BNV ΔB=2 process**

- Neutron spontaneously oscillates into antineutron.
- Search for subsequent annihilation of bound neutron inside nucleus.

- Free oscillation lifetime limit set by **Super-Kamiokande** at 2.7 x 10^8 s at 90% CL. [1]
- **ILL** search in a free neutron beam set limit at 0.86 x 10^8 (90% CL). [2]
- Earlier this month, **SNO** set a free-equivalent limit of 1.23 x 10^8 s (90% CL). [3]

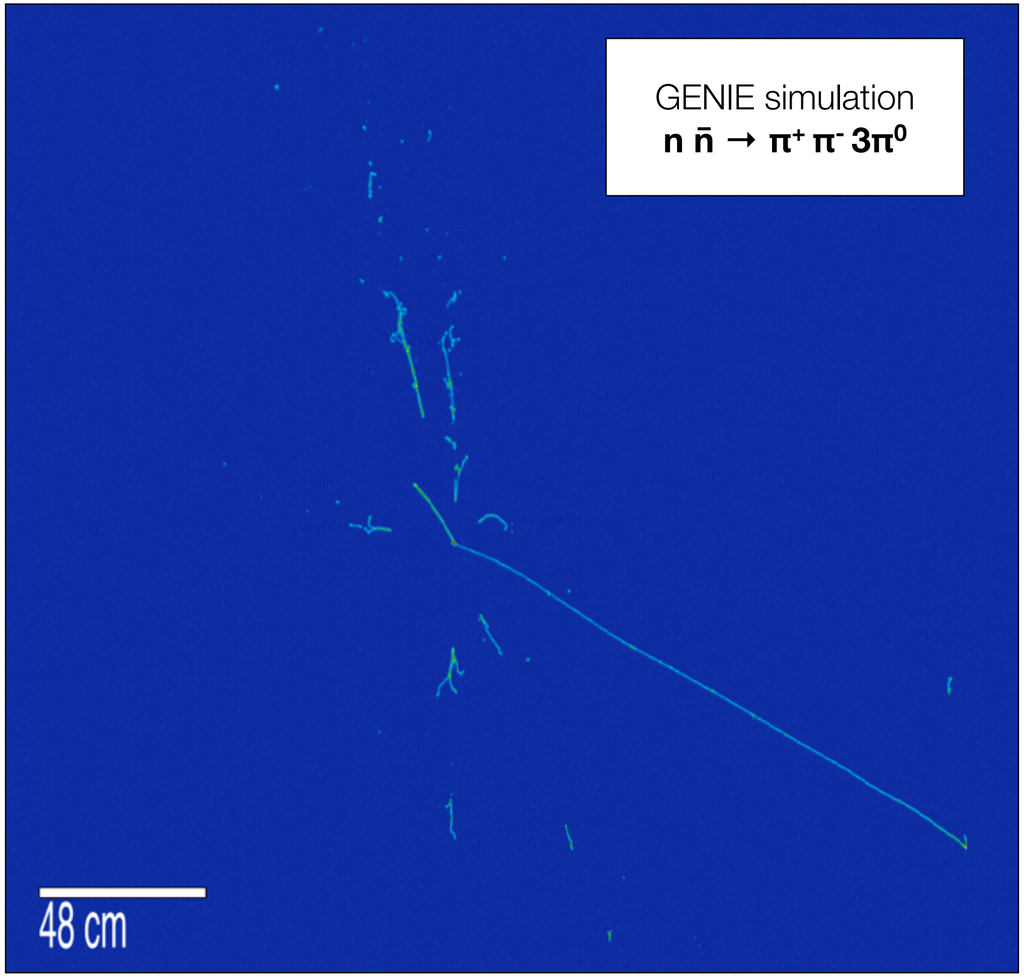


Convert from bound to free lifetime using factor from theory T_R:

$$\tau_{bound} = T_R \, \tau_{free}^2$$

1. arXiv: 1109.4227
2. Z. Phys. C. V63, 409-416
3. arXiv: 1705.00696

n-n̄ oscillation topology



- **Spherical star-like multi-π topology**
- ~2GeV invariant mass.
- Low net momentum.

n-n̄ oscillation event topology

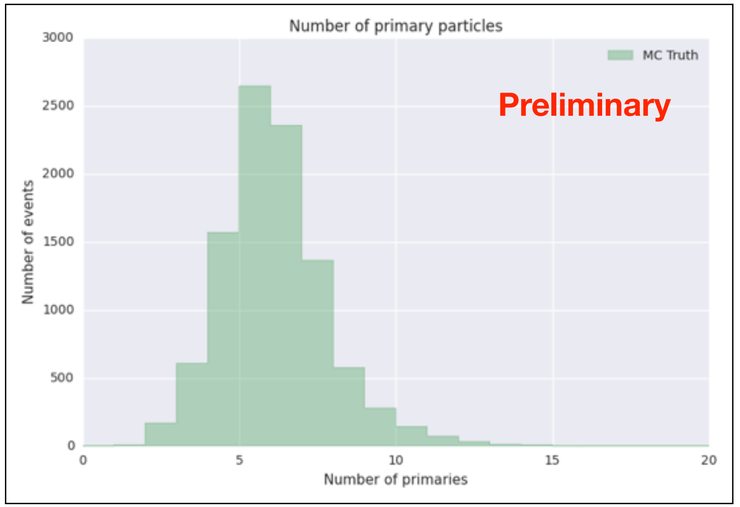
n-n̄ oscillation branching ratios
adapted from arXiv: 1109.4227

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1.2%	$\pi^+\pi^-$	2.0%
$\pi^+2\pi^0$	9.5%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	11.9%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	26.2%	$\pi^+\pi^-2\pi^0$	11.0%
$2\pi^+\pi^-2\pi^0$	42.8%	$\pi^+\pi^-3\pi^0$	28.0%
$2\pi^+\pi^-2\omega$	0.003%	$2\pi^+2\pi^-$	7.1%
$3\pi^+2\pi^-\pi^0$	8.4%	$2\pi^+2\pi^-\pi^0$	24.0%
		$\pi^+\pi^-\omega$	10.0%
		$2\pi^+2\pi^-2\pi^0$	10.0%

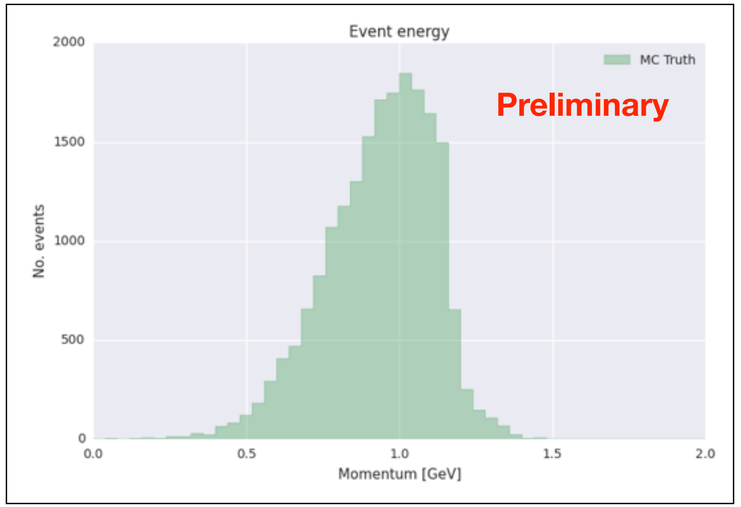
n-n̄ oscillation event generator available in GENIE v2.12 and above.

- Simulates nuclear effects: Fermi momentum, binding energy and final state interactions.

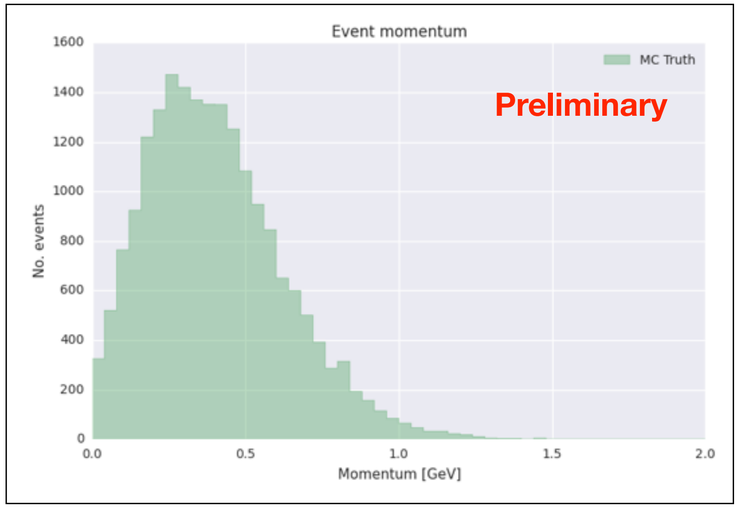
MC truth n-n̄ topology in ^{40}Ar



Number of primary particles



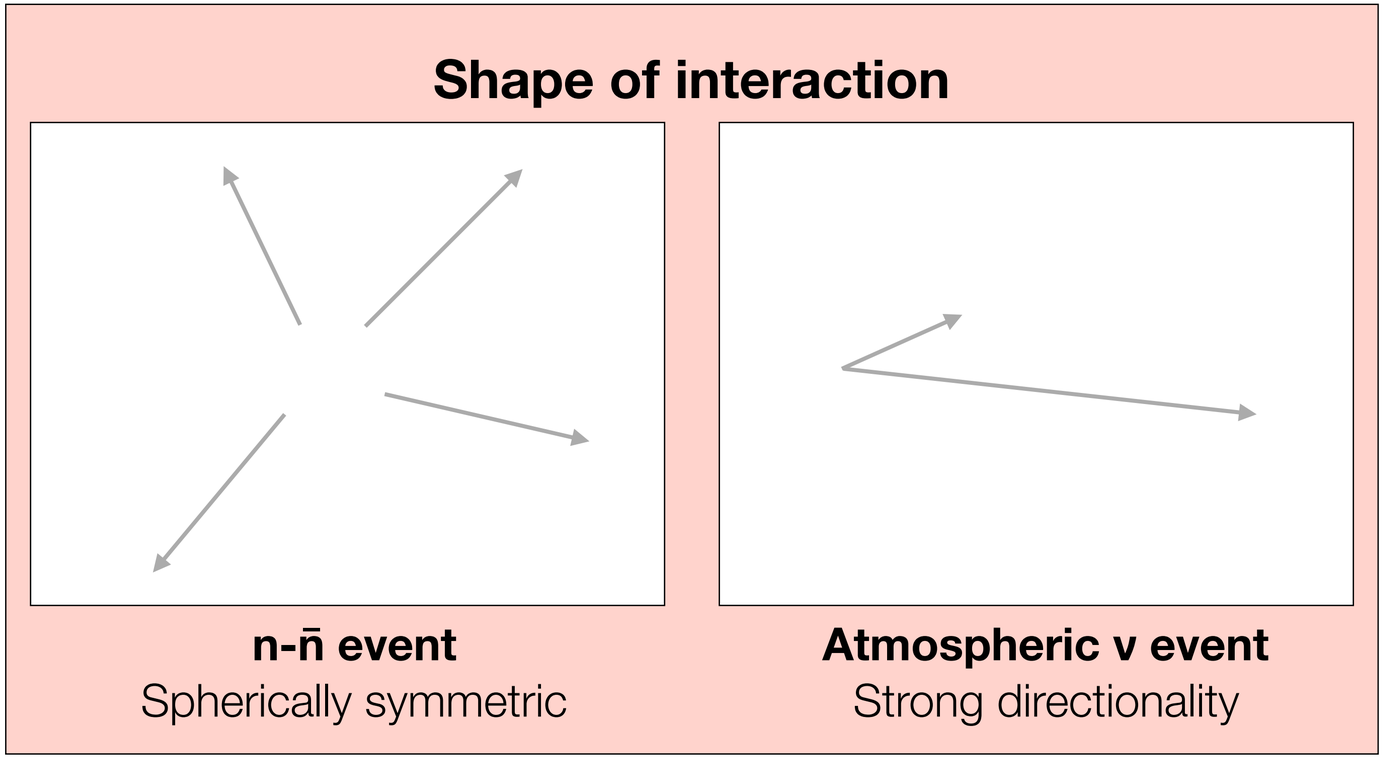
Total event visible energy



Event net momentum

Motivation for convolutional neural network approach

- Dominant DUNE background will be atmospheric neutrinos.
- Traditional identification methods involve reconstructed particles and making cuts on total energy, net momentum, invariant mass.
- **Good candidate for CNN search!**



Simulation

- Use **dunetpc v06_24_00** to generate MC for this study, with DUNE far detector 1x2x6 APA geometry.

Event generator

Signal and background generated in GENIE.

Atmospheric neutrino flux: Honda @ Homestake (unoscillated).

GEANT4 simulation

dunetpc default G4 simulation used.

Detector simulation

Raw digit wires produced with default simulation.

Exponential noise simulation with low-frequency cutoff.

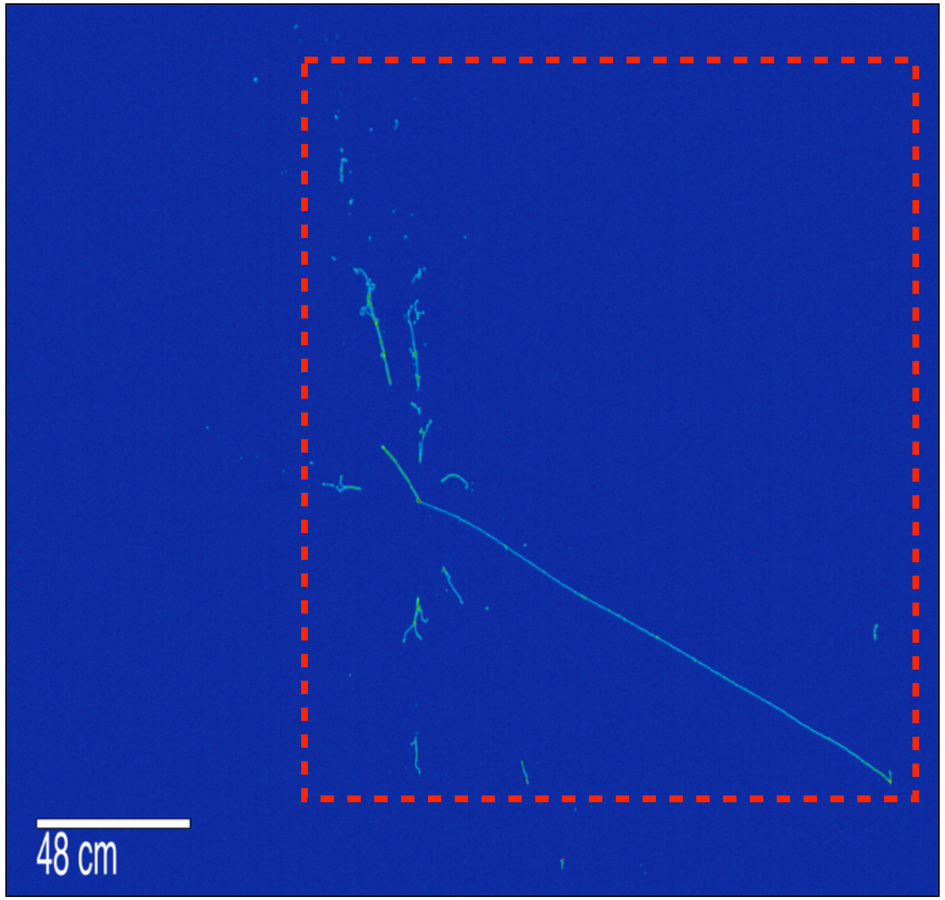
Channels zero-suppressed and empty channels removed.

Wire reconstruction

Deconvolution performed on raw digit waveforms.

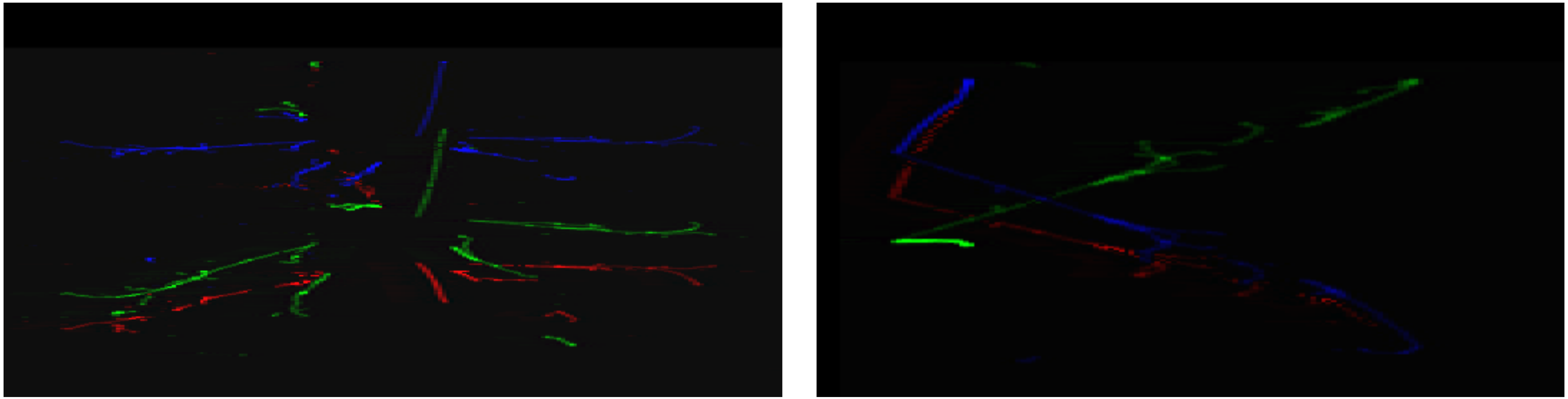
No further reconstruction performed (hit-finding, clustering, object reconstruction).

CNN input production



- DUNE far detector is **modular**, and stitching together multiple modules is non-trivial.
- Select module with largest energy deposition.
- Define a square ROI within this module according to first and last wire and time tick above 20ADC threshold.
- Downsample image to fit inside 600x600 image size.
- Save in CNN-compatible ROOT format.

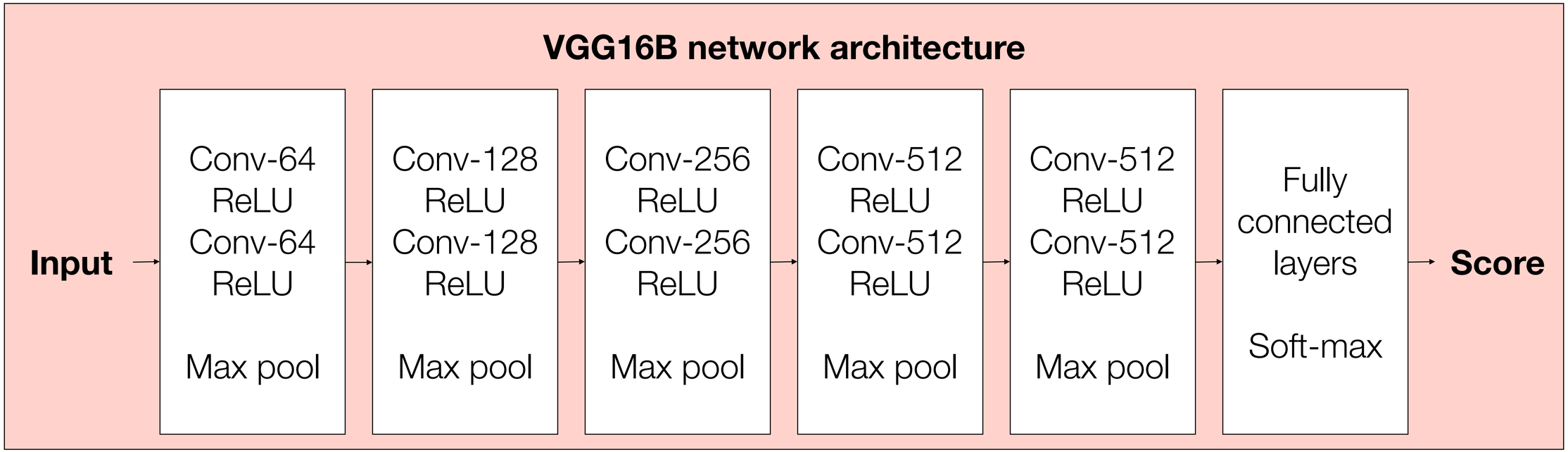
CNN input preparation



- Example signal event (left) and background event (right), with three-plane wire event displays overlaid with RGB information of single image.

Network architecture

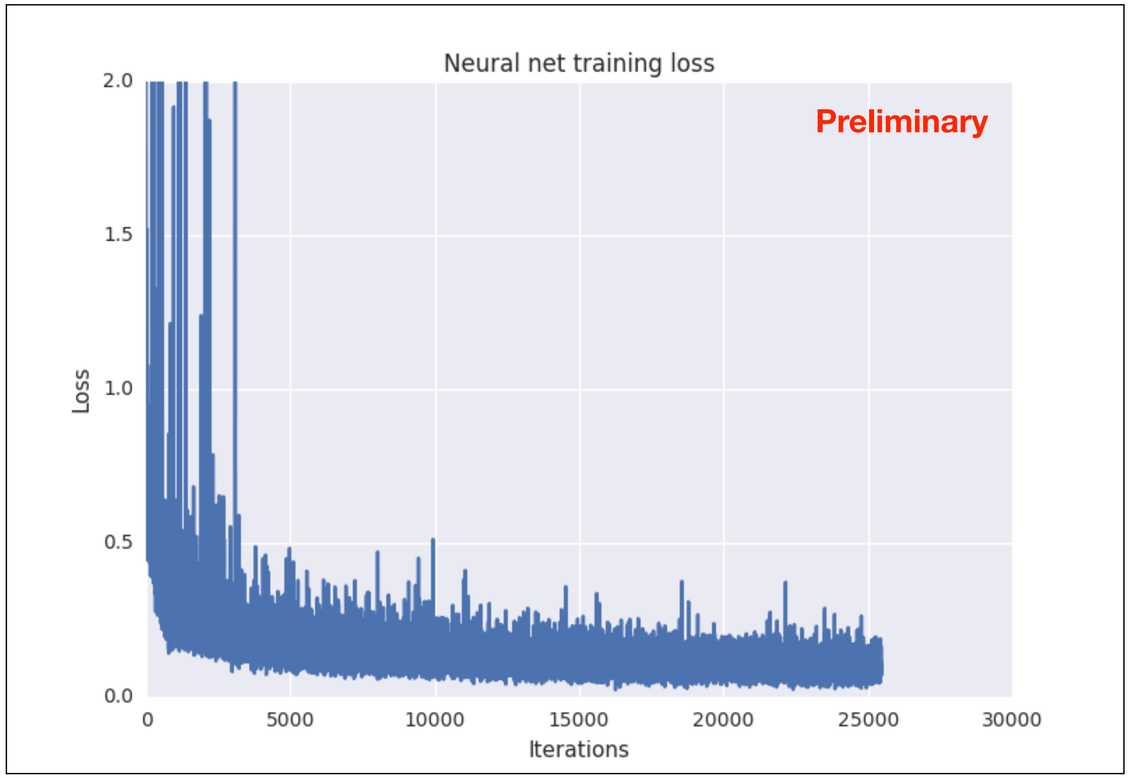
- Use version of Caffe CNN framework[1] modified to interface with LArTPC data files.
- VGG16 [2] network trained with 50,000 signal and background events.

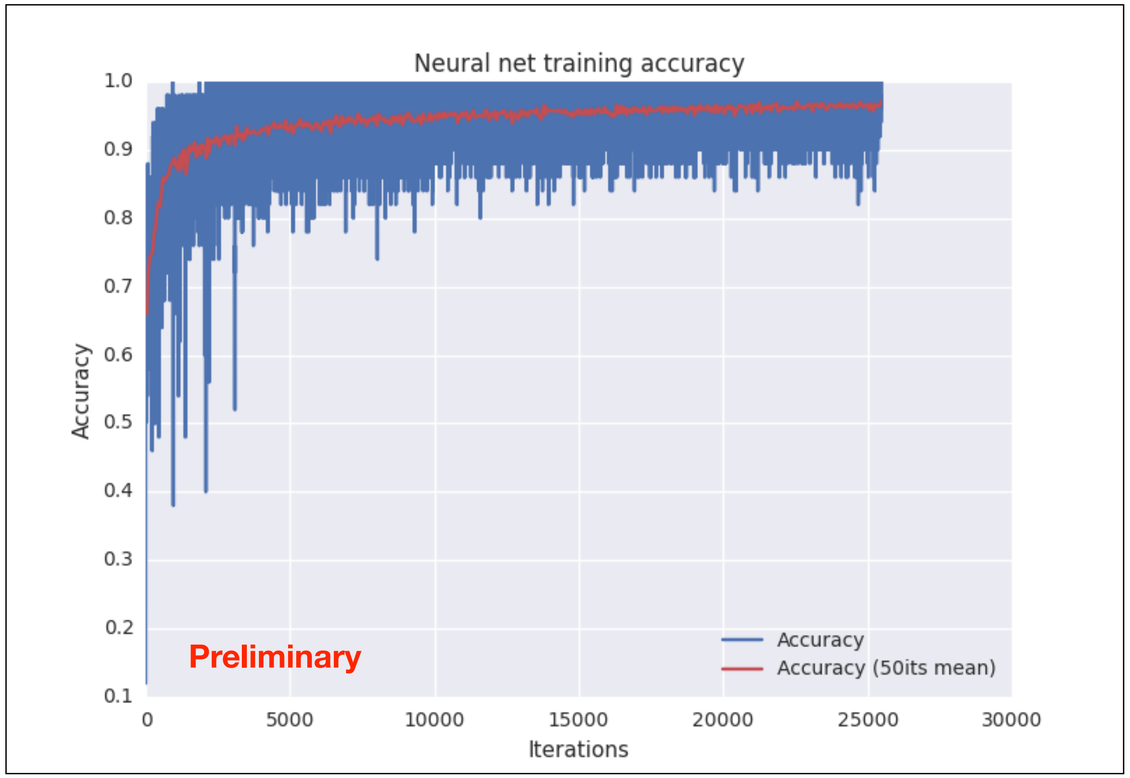


1. arXiv: 1408.5093
2. arXiv: 1409.1556

CNN training

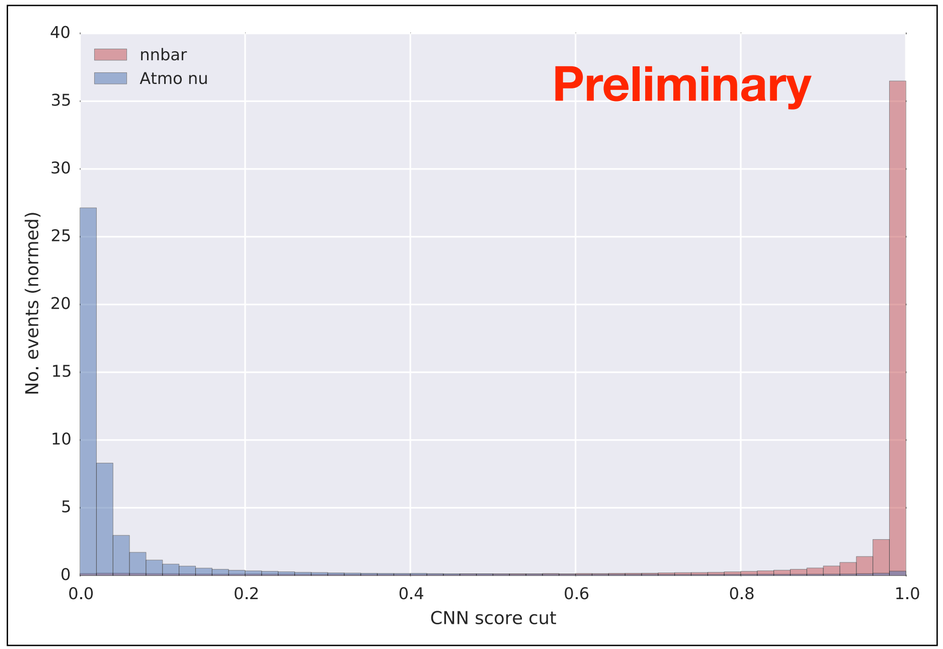
- Training metrics — loss and accuracy — monitored during CNN training.

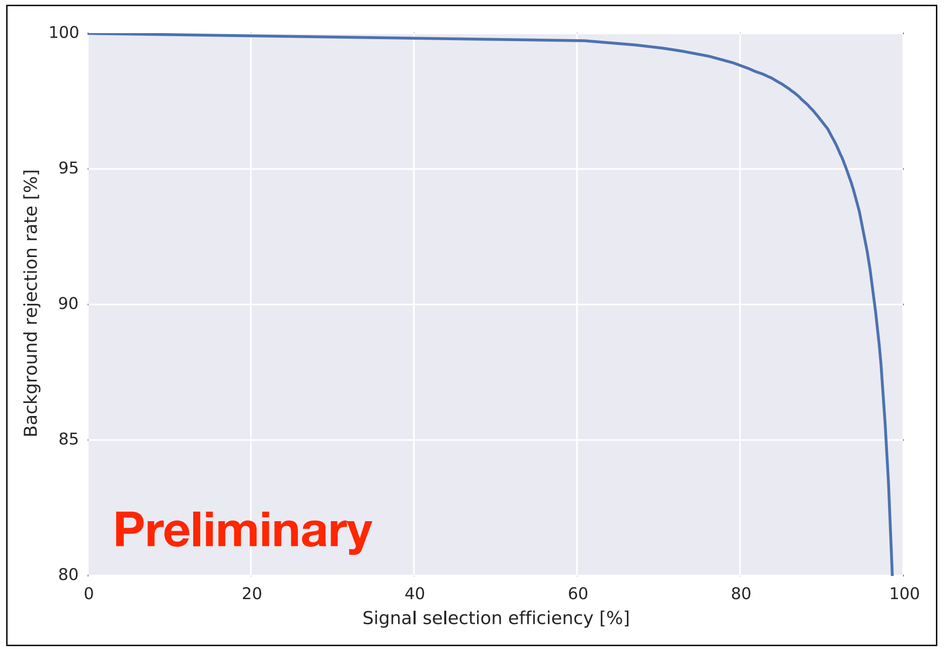




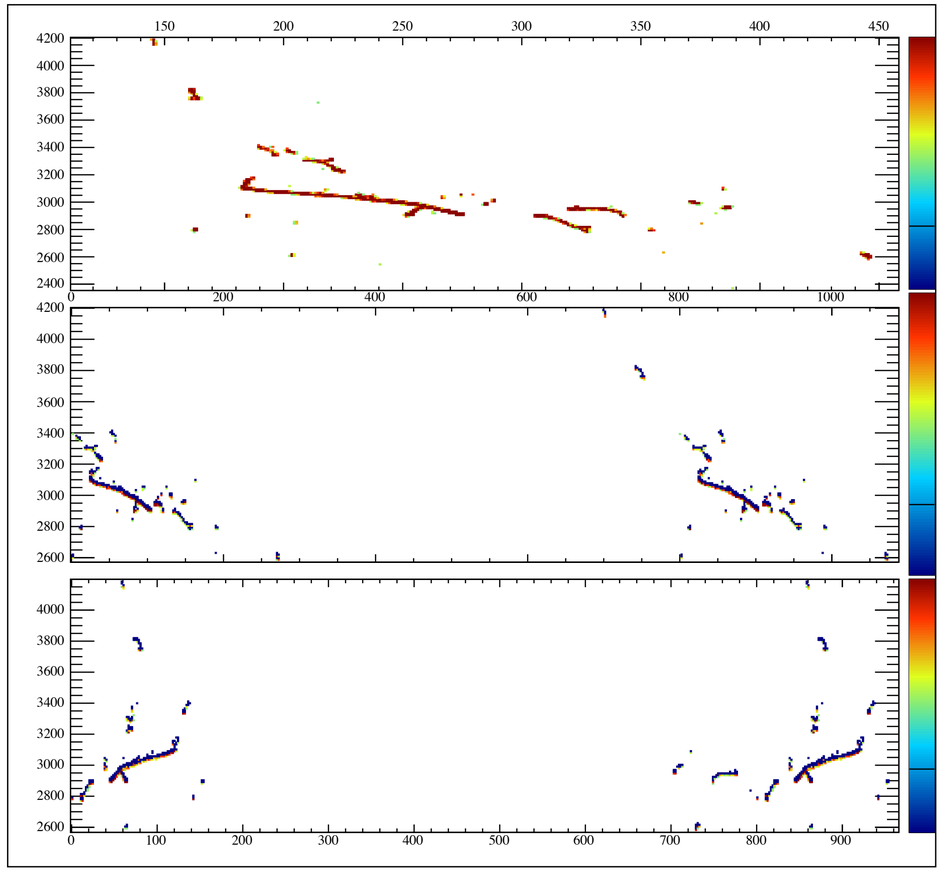
Event classification

- Network performance tested by classifying an independent sample of 200,000 signal and background events.
- Network uses a **Softmax with Loss** layer to score each image between 0 (background-like) and 1 (signal-like).
- Place a cut on this score to yield a signal selection efficiency and background rejection rate.





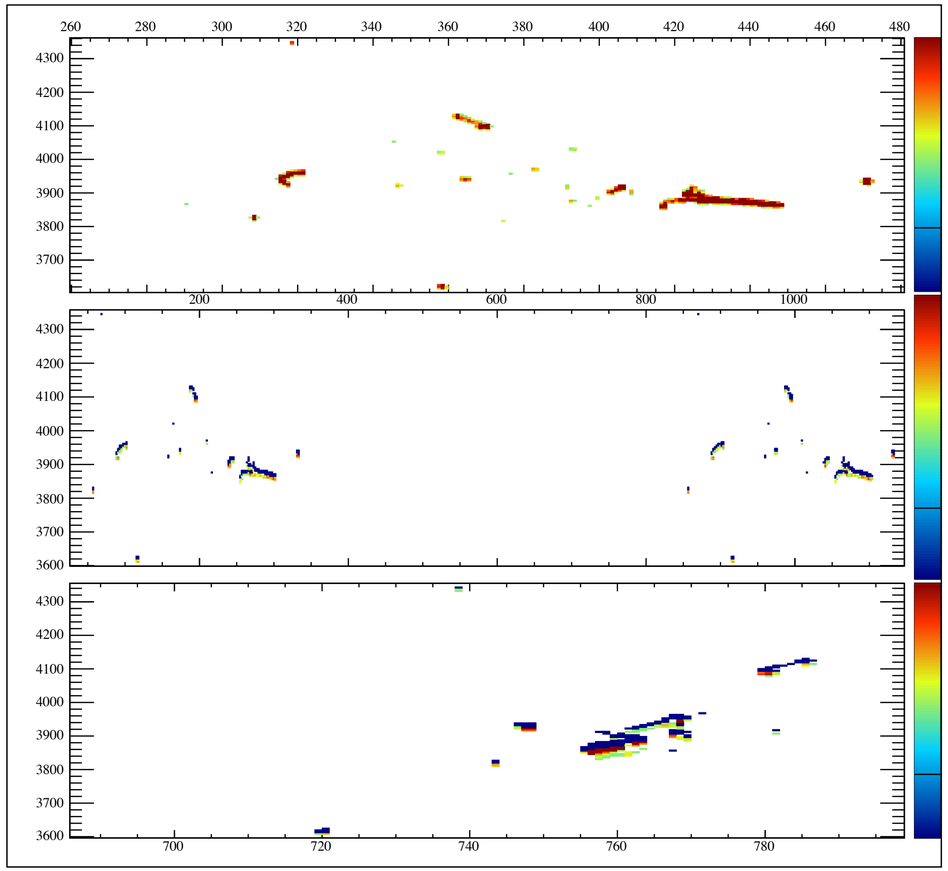
Signal classification — event displays



Well-classified signal event

CNN score: 1

Well-contained, ideal n-n̄ topology

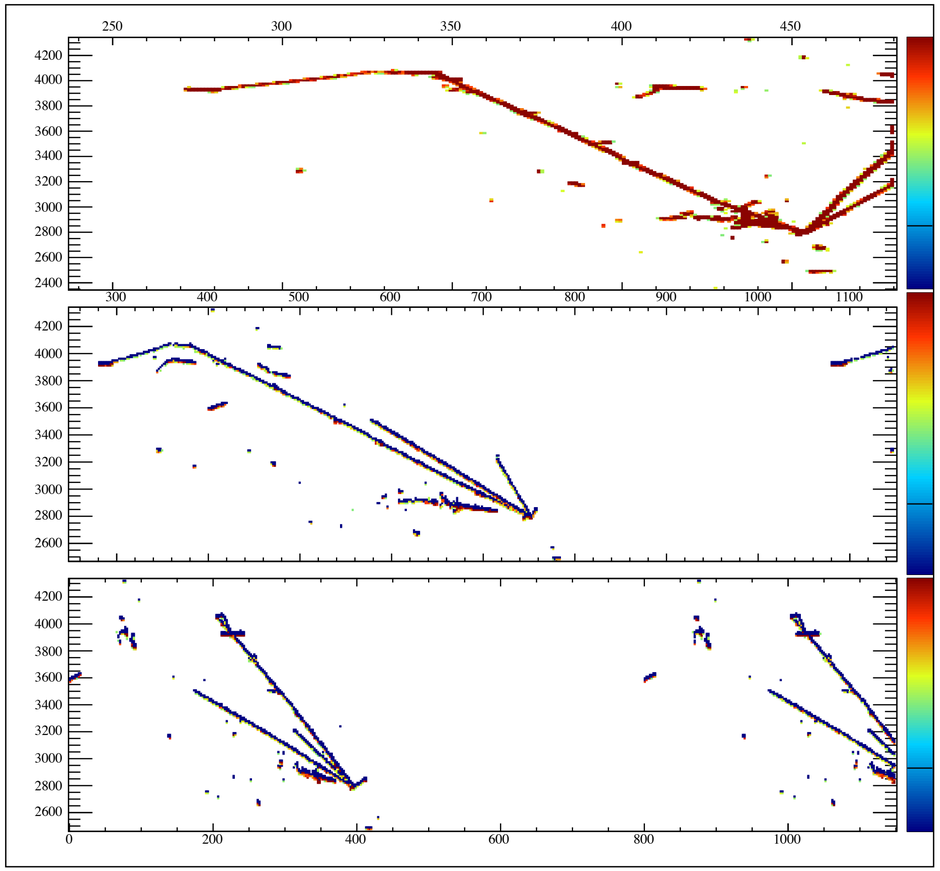


Poorly classified signal event

CNN score: 0.00165

Atmospheric-like n-n̄ topology

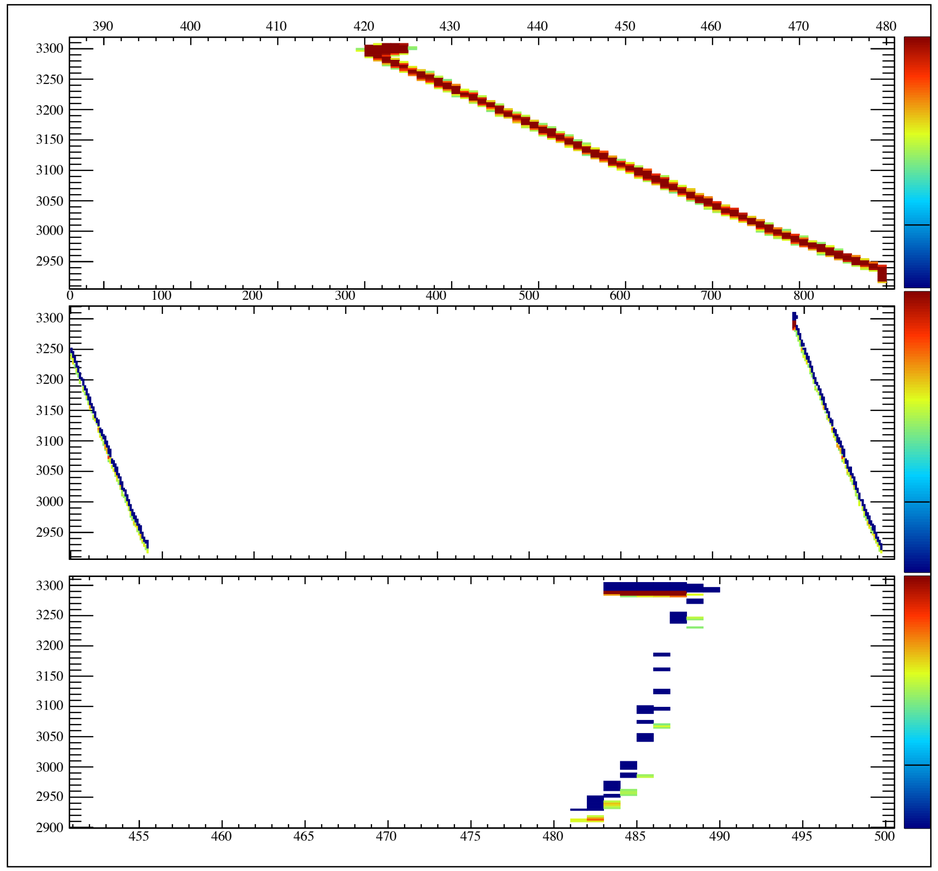
Background classification — event displays



Well-classified background event

CNN score: 0

Highly directional atmospheric ν topology

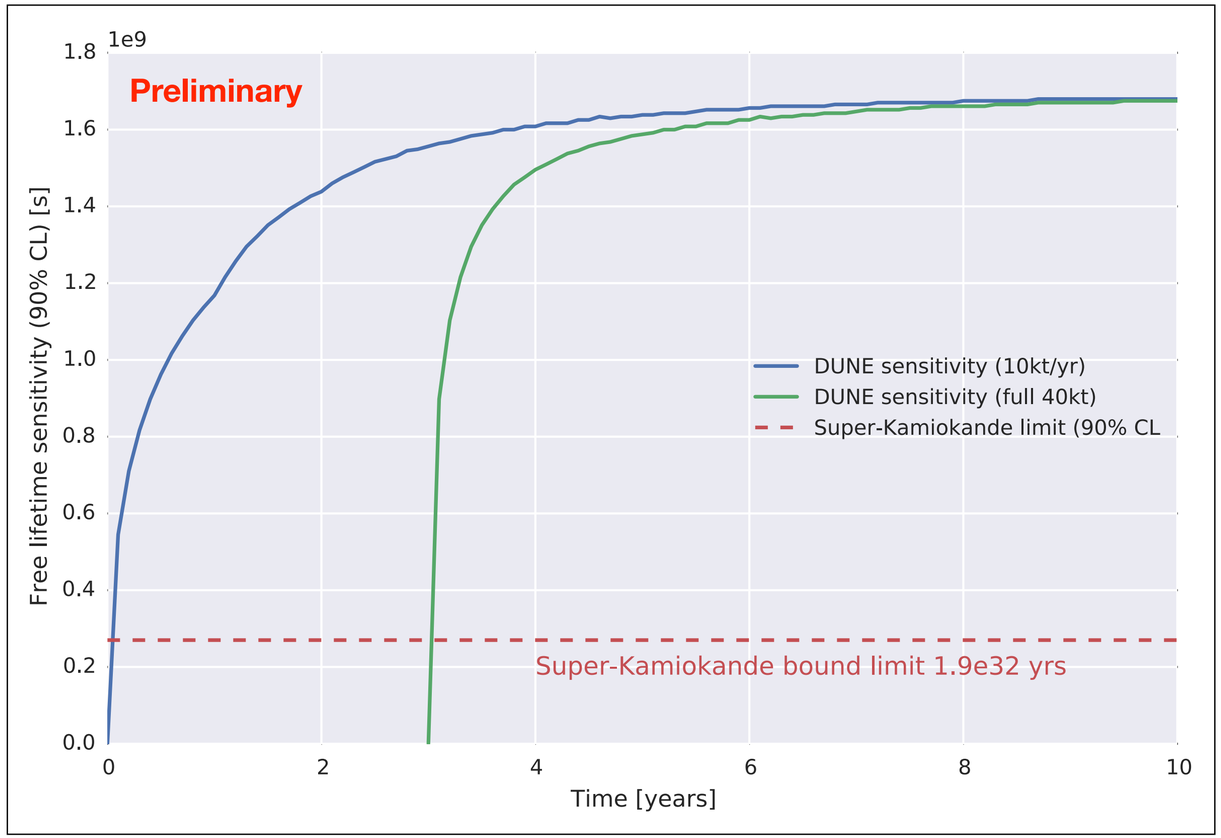


Poorly classified background event

CNN score: 0.9999573

Poorly contained atmospheric ν topology

DUNE n-n̄ sensitivity



Projected DUNE sensitivity
Optimised CNN score cut, 10 years exposure

- Optimised cut on CNN score of **0.999966** provides a signal selection efficiency of **18.1%** and a background mis-ID rate of ~$\mathbf{10^{-5}}$.
- At this efficiency and background rate, DUNE's sensitivity is **1.7 x $\mathbf{10^9}$ s** (90% CL) after 10 years running.
- Factor ~5 improvement over current best limit, **2.7 x $\mathbf{10^8}$ s** (90% CL) from Super-Kamiokande.
- A far more conservative cut of **0.99** equates to a sensitivity of **4.2 x $\mathbf{10^8}$ s** (90% CL).

Discussion

- This approach shows great promise as an event selection tool in LArTPCs.
- Currently refining and carrying out follow-up studies:
  - Use oscillated fluxes, which will include tau neutrino background events.
  - Investigate effect of requiring all events are fully contained in APA.
  - Vary noise simulation to understand systematic uncertainties.
- Other ways to extend and improve this study:
  - Fine-tune training.
  - Correlate information across wire planes.